Product Information Exchange: Practices and Standards

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Abstract

The paper discusses the evolution of product information exchange from point-to-point exchange of geometry between Computer-aided Design (CAD) tools through today's suite of tools and processes of Computer-aided Product Development (CAPD) to the future fully integrated Computer-aided Product Realization (CAPR) process. The categories of processes and the layers of information exchange are reviewed. The current practice in product information exchange, the relevant information exchange standards, and near-future plans for improvements are presented. The major recent demands on more comprehensive product information exchange are discussed in terms of the exchange of non-geometric information and support of feature-based design, knowledge-based engineering and management of product variety. Two conceptual frameworks for the support of CAPD and CAPR, representative of current research, are briefly sketched. Finally, a conceptual model of product information exchange is presented so as to define the range of implementation and standardization paths that may be taken in the future.

1. Introduction

The 25 years since the Computers and Information in Engineering Division was founded have witnessed a rapid growth in the use of computers by engineers. Computer tools for design have evolved from aiding 2D drafting to providing comprehensive 3D modeling capabilities. Functional analysis, once reserved for the final design verification of the most critical components, is now routinely used in even early stages of design to guide the design process. The evolution toward knowledge-aided and immersive environments will continue. The trend toward distributed design activities and more heterogeneous tools will necessitate robust information exchange mechanisms between the participants in design and, more broadly, in the entire product development and realization process.

In this paper, we distinguish three levels at which computer-based information is generated, used and exchanged, as follows:

1. **Computer-aided Design** (CAD) or traditional CAD refers to the processes and tools for defining, elaborating and modifying the geometry or spatial description of a product being designed.
2. **Computer-aided Product Development** (CAPD) refers to the collection of engineering processes and support tools that move the product definition from the initial user requirements or specifications received by the engineering department to the complete and fully evaluated description ready for transmittal to the manufacturing department.
3. **Computer-aided Product Realization** (CAPR) refers to the totality of business

processes, of which engineering is one, that deal with the full lifecycle of the product from the earliest ideation to the product's final disposal.

The paper traces the role of product information exchange at these three levels and illustrate past, present and future practices and the standards that govern their use. The first level, CAD, has become ubiquitous in the last 25 years and is well supported by education and training programs, a vibrant and competitive software support industry, and research in computational geometry and human-computer interaction. CAD to CAD information exchange is discussed in Section 4. From this point, primary emphasis is on the second level, CAPD, where much of the information exchange development and standardization are currently taking place. Elements of the full CAPR information exchange support are introduced where warranted by the context, although this area is still in an era of rapid flux.

Outline of the Paper. The past and present are discussed in Sections 2 through 4 in terms of the categories of CAPD processes, layers of information exchange and information exchange practices, respectively. The future is sketched in Sections 5 through 7 in terms of the new demands on product representation and information exchange, an illustrative set of new developments responding to some of the demands and a conceptual model of the elements of information exchange and their relationships, respectively. The paper concludes with a summary in Section 8.

2. Components of Computer-Aided Product Development

This section describes the components of a Computer-aided Product Development (CAPD) system in today's computing environment. The components are illustrated in Figure 1, and described in the following subsections; detailed discussion of the individual components and of the research supporting these is out of the scope of this overview paper.

The components of the CAPD, shown in the figure, can be broadly classified into: engineering process support tools; repositories; and network infrastructure. The paper discusses the first two elements. The third element, network infrastructure, includes all the components required to support the movement of various kinds of engineering data, information, and knowledge through the entire product life cycle.

2.1 Engineering Process Support Tools

Computer support tools used in the various phases of engineering design fall under this category. Representative tools are discussed in the following paragraphs.

Engineering Specifications. This process involves mapping the customer requirements into engineering requirements, refining the engineering requirements in consideration of the relevant laws, regulations, product standards, etc., and considering the existing patents in the area [1, 2]. The process is largely supported by generic tools such as spreadsheets and custom applications.
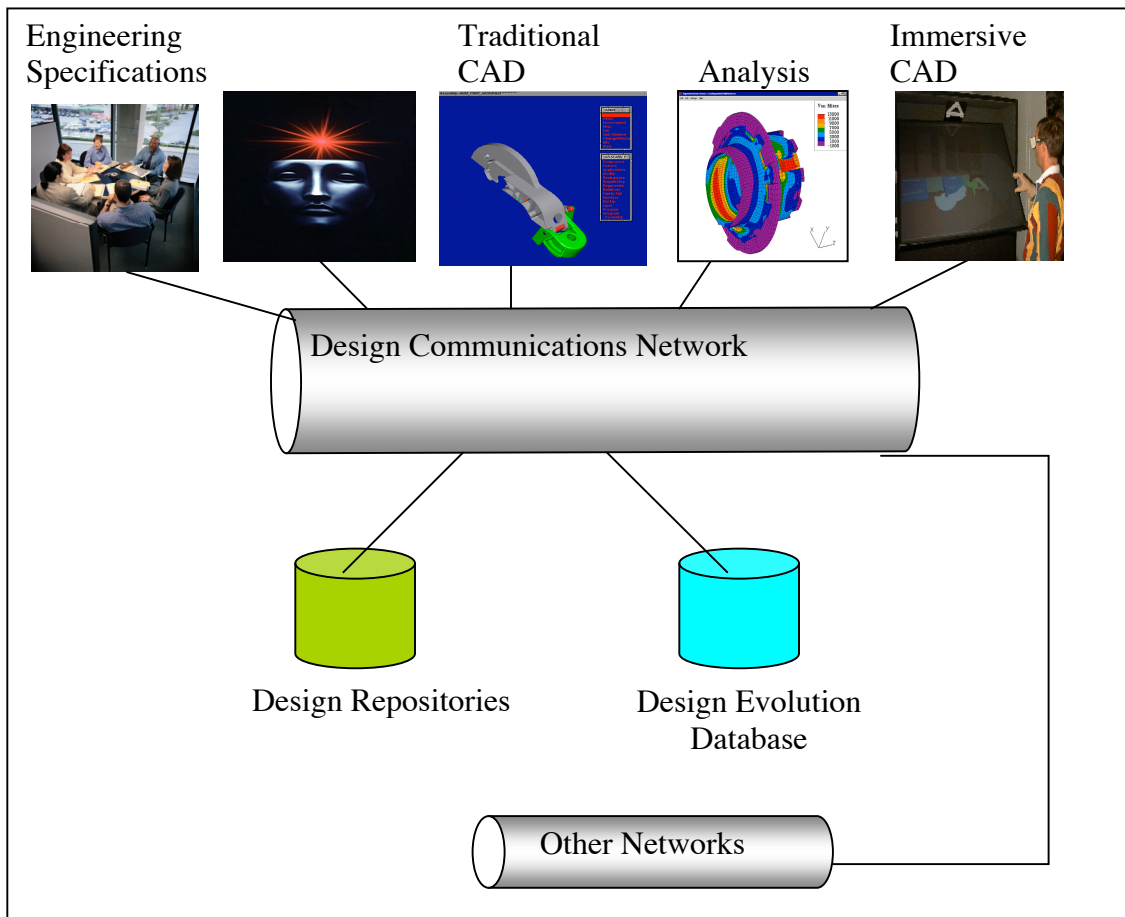
Figure 1: Components of Computer-Aided Product Development (CAPD)

Knowledge-based CAD. One class of knowledge-based CAD tools helps designers to reason in terms of function first so that the product's form subsequently results from function. Knowledge-based design or synthesis systems first focus on the symbolic aspects of design and later assist the designer in mapping the symbolic structure to a geometric model [3].

Traditional CAD. Traditional CAD systems initially evolved out of attempts to provide better drafting aids. In these systems, the designer uses the computer to develop either 2D or 3D spatial models of the design [4, 5]. The drawback of traditional CAD systems is that they only aid in generating geometric forms. This limitation encourages designers to come up with the form of the product first, an approach that can result in non-optimal designs.

Analysis. Computer-aided engineering (CAE) analysis tools, such as kinematic, finite element and computational fluid mechanics analyses, focus on the functional analysis and evaluation of behavior of the designs [6, 7].

Immersive CAD. In immersive CAD, the human being becomes part of the design by using various immersive environments, including virtual displays and haptic, visual and speech interfaces [8]. Immersive CAD systems can aid in the evaluation of the operability and manufacturability of proposed designs. With appropriate interfaces, designs can be directly modified to reflect the designers' experience in manipulating the virtual prototype.

Most of the current CAD system market has focused on the traditional geometry-based CAD and the CAE analysis domains. Although knowledge-based CAD gained some visibility in the early 1990s, its impact is yet to be realized.

2.2 Repositories

Several types of repositories, such as catalogs, regulatory information, design case histories, product data management systems, are used during the design process. We describe two representative repositories.

Design Repositories. Design repositories are the electronic substitute for and successor of the traditional file cabinets where information on past designs is stored. Design repositories store descriptions of past designs, together with their rationale, in a form suitable for browsing and retrieval for direct use in the active design process [9]. Since design descriptions contain the products' hierarchical decomposition, parts and components of previous products can be readily extracted for reuse.

Design Evolution Databases. The representation of the design as it evolves is maintained in design evolution databases, together with all relevant documentation [10]. In rare cases, the entire design database may reside in one place and be homogeneous. More frequently, it will reside on distributed and heterogeneous systems, information structures or information models. Nevertheless, the database management system must present every user with the information he/she needs in the format that the user familiarly uses. This may necessitate syntactic as well as semantic translations of information passing to or from the database.

Product data management (PDM) systems provide some of the functionalities of design evolution databases. In the recent past, vendors have been refocusing their strategy towards Product Life Cycle Management (PLM) systems supporting CAPR.

3. Layers of Information Exchange in Computer-Aided Product Development

For nearly two centuries, from the time Gaspard Monge published his "La Geometrie Descriptive" in 1801, the primary means of communication between engineers has been the paper mechanical drawing. During the last 25 years, the available communication media have drastically changed due to the rapid proliferation of computer-aided design/manufacturing (CAD/CAM) tools.

In a networked enterprise, the information exchange of tools, information, and models becomes increasingly important for the close integration of engineering. CAD systems must communicate with CAE tools to facilitate engineering analyses in the design process. CAD systems must communicate with CAM systems to provide a smooth transition from design to manufacturing. CAM systems must communicate with numerically controlled (NC) machine tools to execute the manufacturing activities. CAD systems must communicate with PDM and PLM systems to ensure proper product configuration control.

Information exchange between various tools does not occur in a single layer. Information exchange between heterogeneous engineering tools involves several layers. These layers, patterned after the layered computer system architectures, are described in the following paragraphs.

Physical. This layer is concerned with the physical transmission medium, such as Ethernet or fiber optics.

Object. At this layer, engineering objects are transported using appropriate object transfer modes, such as CORBA (Common Object Request Broker Architecture), EJB (Enterprise Java Beans) or COM (Common Object Model) or by using SOAP (Simple Object Access Protocol). At this layer, objects do not carry any of the engineering significance or semantics crucial to the next layer; they are simply syntactically correct aggregations or "bundles" of data to be transmitted. This entire layer is hidden from users, and often even from application programmers, by being incorporated in middleware.

Content. This layer communicates engineering product information, and includes information about features, constraint, materials, processes, etc. in addition to geometry. Information at this level can be expressed in an appropriate modeling language, such as EXPRESS[1] used by STEP, KIF (Knowledge Interchange Format)[2] or XML (Extensible Markup Language)[3]. The focus of this paper is on this level. We discuss the various standards for the Content level in more detail in the following section and the range of available modeling languages in Section 7.

Design Rationale. This layer deals with design rationale and design history issues, providing additional information (including inference networks, plans, goals, justifications, etc.) about the engineering objects in the Content layer. Issues for this layer are addressed in [11].

Communication. This layer provides additional detail to the Content and Design Rationale layers. Such details include the specification of engineering ontologies used, sender and recipient identification, security information, etc. [12].

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[1] http://www.tc184-sc4.org/
[2] http://logic.stanford.edu/kif/kif.html
[3] http://www.w3.org/XML/

Negotiation. Any multi-agent activity will involve negotiations. Information needed to be exchanged in such negotiations, such as arguments, alternatives, comparisons and resolutions, is defined in this layer [13,14, 15].

4. Current Practice of Content Layer Information Exchange in Computer-Aided Product Development

In this section, the current practice in product information exchange, relevant standards and near-future plans for improving product information exchange in Computer-aided Product Development (CAPD) are discussed. The major information exchange paths are depicted in Figure 2 and are addressed in the following subsections, with illustrative examples of the available standards and protocols.

CAD-CAD Information Exchange. Before the advent of three-dimensional parametric design, a large number of commercial CAD tools and in-house software developed by manufacturing enterprises was in use. The information created with one CAD system was not interchangeable with other systems and their internal databases. An effort to create a standard for the exchange of CAD data began in 1979; this standard became IGES (we refer the reader to [16] for an excellent history of IGES and STEP). The fundamental idea of IGES was to transfer two-dimensional drawing data, later including three-dimensional shape data, in a fixed file format in electronic form. Limitations of the IGES standard soon became apparent: large file sizes, long processing times, lack of upward compatibility and, most importantly, the restriction of information exchange to shape data only. Despite these limitations, IGES is still supported by most CAD products and widely used for CAD information exchange.
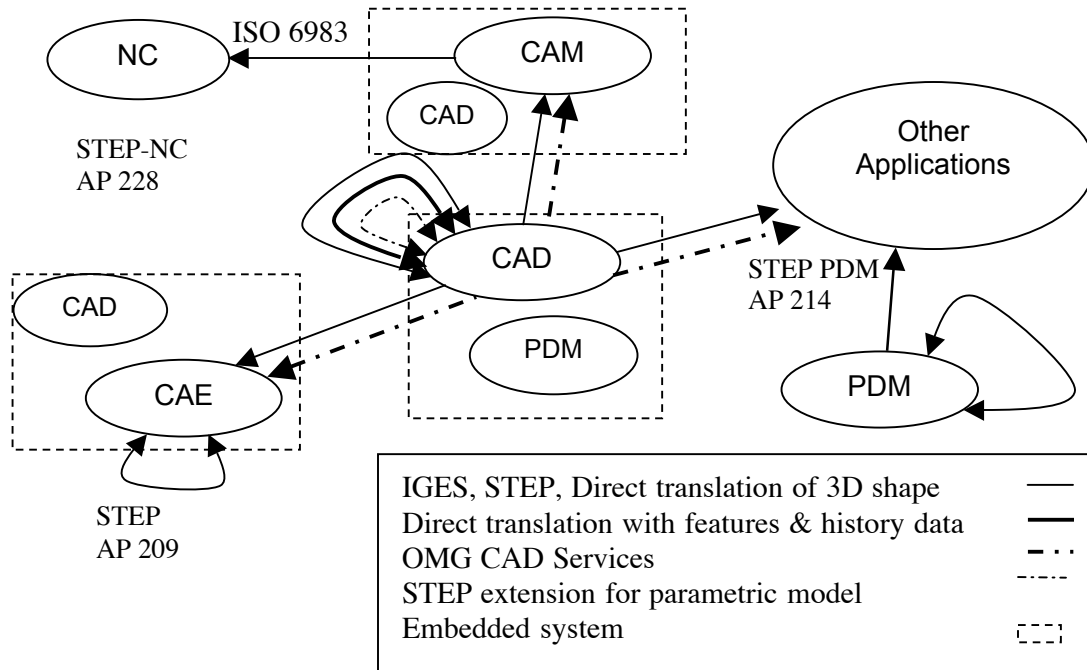
Figure 2: Data Interchange Map between CAPD Processes

The idea of utilizing a geometric modeling kernel for developing CAD products emerged in 1987. The first commercial modeling kernel, ACIS, appeared in 1990. Later, similar kernels, such as Parasolid, Designbase and Open CASCADE became available as products (see [17,18,19] for comparisons of these and other tools). It was contemplated at one time that the issue of exchanging three-dimensional shape data might be solved if one of the kernels were widely adopted for CAD product development, but this never happened. However, three-dimensional solid shape information exchange with a kernel-based data format, such as the '.sat' files used by ACIS, is supported and used between CAD products that utilize the same modeling kernel.

A comprehensive standardization effort for the representation of product information began in 1984. This new standard was targeted to provide a mechanism for the exchange of lifecycle product information in computer interpretable electronic form. The resulting international standard, ISO 10303, was named STEP (Standard for the Exchange of Product model data) and was developed by the International Organization for Standardization Technical Committee 184/Subcommittee SC4 (ISO TC 184/SC4) [16]. One of the significant departures from existing standards was that a formal information modeling technology was adopted to represent information in the standard, instead of using fixed file formats.

STEP is intended to enable the exchange of product information between different modules of a product realization system. The first parts of STEP to achieve International

Standard status were published in 1994; many other parts have since been published or are under development and will eventually be added to the standard[4]. STEP consists of many parts and can be viewed as consisting of several layers. The top layer consists of a set of application protocols (APs), which address specific product classes and life-cycle stages (e.g., mechanical, electronic, ship or automotive design, process planning). These APs specify the actual information exchange, and are constructed from a set of modules at a lower layer, called integrated resources, which are common for all disciplines. Other parts specify standard mechanisms for the actual transfer of data, the conformance testing methodology, and various test suites.

The STEP AP most relevant to traditional CAD systems is AP 203, "Configuration Controlled 3D Designs of Mechanical Parts and Assemblies." This protocol defines the information exchange of geometric entities and configuration control of products. AP 203 defines several levels of implementation – called conformance classes – which provide increasing levels of coverage. PDES, Inc.[5] and ProSTEP AG[6] are two representative organizations devoted to accelerating the development and implementation of STEP. These organizations examine commercial products for STEP translation capabilities and reports the results periodically. For example, the PDES, Inc. website has a current list of the implementation status of several STEP application protocols. Also, US PRO, a nonprofit membership organization established by industry, began STEP certification in 1998[7]. STEP-certified products are those that have successfully completed a formal evaluation of the product's adherence to the STEP standard in accordance with the testing procedures and guidelines that form a part of the standard. For various economic impact studies of the STEP standard (and other related topics) see http://www.mel.nist.gov/msidlibrary/impact_studies.html.

The primary emphasis of STEP AP 203 is on shape description plus product configuration data. Facilities are provided for capturing, in standard format, the following representations: 2D drawings, 3D wireframes, surface models and solid models. This reflects the state of CAD technology as it was when the STEP development effort began in the mid-1980s. However, CAD technology has progressed since that time, and most major CAD systems now provide facilities for parametric, variational design (including constraints) and/or feature-based design. In addition, many of these systems have facilities to record design histories. These systems generate additional information, beyond the pure shape descriptions created by older systems. STEP AP 203 Edition 1 did not provide any means for capturing and transmitting this additional information. The short term parametrics effort under Working Group 12 (WG 12) of ISO TC 184/SC4 is addressing this problem. WG 12's efforts include Part 108 for parametric information and Part 111 for construction history encoding. Attempts are being made to incorporate these parts into STEP AP 203 Edition 2, which extended STEP AP 203 for supporting GD&T (geometric dimensioning and tolerancing), colors, layers, material data, etc., was released

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[4] Recent updates (and other relevant details) can be found at the following website: http://www.tc184-sc4.org.
[5] http://pdesinc.aticorp.org/vendor/CAD_vendor.html
[6] http://www.prostep.com/en/
[7] http://www.uspro.org/

in 2004. There is also related work in visualization standards. As our focus is on information exchange standards we will not discuss such standards, and we refer the reader to [20] for such a review.

In response to the urgent need for parametric CAD information exchange, vendors provide translators for exchanging product information, including feature, history, and constraint information, with their own proprietary technology. Proficiency[8], TTI[9], Theorem Solutions[10], ITI[11] and InterOp[12] are among the providers of functionalities for exchanging native feature and history data between major CAD products.

Accommodation of Legacy CAD Data. Translated data from other 3D CAD systems or static data in legacy databases are hard to edit and utilize further within modern parametric feature-based CAD systems. Some CAD tools offer feature recognizer modules for building native parametric feature-based data automatically from static 3D data[13]. The data generated this way may not represent exactly the original designer's intention or modeling process, but at least it allows easier modification of the model. SolidWorks[14] and Solid Edge[15] are among the traditional CAD systems that provide feature recognition modules for this purpose. In addition, tools such as Honeywell's FB-Mach take as input a geometric model of a part and output its various features [21].

CAE-CAE Information Exchange. Analysis systems typically have their own proprietary interfaces and internal representations for preparing analysis models and representing analysis results. Occasionally, input information formats of the more popular analysis software have been supported by other systems. However, design and collaboration on a product model in an extended enterprise necessitated a standard for describing analysis data[16]. STEP AP 209 provides a neutral data format representation of analysis models needed for conducting engineering analyses using heterogeneous analysis tools. STEP AP 209 enables version control of design and analysis information linked to a product structure; it is thus a powerful CAD/CAE information exchange aid as well. STEP AP 209 has been approved as an international standard and is expected to be widely supported by analysis systems in the near future.

PDM-PDM Information Exchange. Collaboration on product information in an extended enterprise also necessitates a standard for describing product information within PDM systems. The ISO 10303 STEP AP203/214 PDM Schema provides a reference information model for the exchange of a central, common subset of the data being managed within PDM systems (see the ISO website--http://www.tc184-sc4.org/--for more information on AP 214). It represents the intersection of requirements and

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[8] http://www.proficiency.com/
[9] http://www.translationtech.com/
[10] http://www.theorem-usa.com/
[11] http://www.DEXCenter.com/
[12] http://www.spatial.com/
[13] //www.mmsonline.com/articles/040101.html
[14] http://www.solidworks.com/html/Products/featureworks.cfm
[15] http://www.solid-edge.com/prodinfo/prod_featurereq.htm
[16] http://pdesinc.aticorp.org/pilots/engineering.html

information structures from a range of STEP application protocols, all generally within the domains of design and development of discrete electro/mechanical parts and assemblies.

CAD-CAE Information Exchange. Some CAE analysis tools have their own modeling interfaces, not compatible with other systems; however, most FEA analysis tools offer capabilities for importing 3D shape data from CAD systems (see [22] for a survey of CAD-CAE integration efforts). Major vendors of CAD systems offer FEA modules embedded within CAD tools, providing a convenient user interface for the transfer of 3D shape data from the CAD system to the FEA module. Most independent FEA tools provide data interface modules for major native CAD data formats and for standard formats such as IGES and STEP. STEP AP 209, discussed above, provides explicit linkages between the shape information in the design (i.e., CAD) and analysis models.

Successful import of geometric information from a CAD system to a FEA tool does not guarantee a successful analysis. There are two categories of practical problems that impede the smooth integration of CAD and analysis tools. The first category deals with improper geometry information that is not suitable for processing in the analysis, mainly due to erroneous practices of CAD operators and to problems resulting from data translation. This kind of problem can be solved by properly training CAD operators and by using geometry analysis or fix/healing tools such as GeometryQA[17] and CADfix[18]. The second category deals with the fact that the models needed for analysis are different from the detailed 3D design models. Often, a significant amount of time is consumed in idealization or remodeling for analysis after the detailed 3D design is finished. This effort can be reduced by the feature suppression capabilities of some CAD tools and/or supplementary modeling tools such as mid-plane or medial axis extraction. Representative projects addressing this issue are described in [23] and [24].

CAD-CAM Information Exchange. Information exchange between CAD and CAM tools is achieved by taking the detailed geometry of the part (generally a boundary representation), performing various operations on the geometry, and then using the modified geometry as an input to an appropriate CAM tool; some CAM tools may directly operate on the boundary representation, while others (e.g., Numerically Controlled [NC] machines) operate on features (which are extracted using an appropriate tool described earlier). In the case of NC machining, most of the problems encountered during code generation are related to geometry details, such as surface discontinuities due to different tolerances between CAD and CAM tools, and cracks, sliver surfaces, duplicate surfaces, reversed surfaces, etc., due to CAD operators' poor practices. These problems can be solved by properly training CAD operators and by using geometry analysis or fix/healing tools. Current CAM tools provide information interface for IGES, STEP and major native CAD formats and generate ISO 6983 G-code for NC controllers. A new initiative, ISO 10303 AP 228, informally known as STEP-NC, is being carried out in the STEP community to develop a standard for more streamlined and intelligent interfaces between CAD and CAM, which will eventually make ISO 6983 obsolete.

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[17] http://www.prescienttech.com/PROD/entsolgeometry.html
[18] http://www.cadfix.com/

With the new standard, future NC controllers will operate on 3D shape data and high-level machining operations instead of direct commands for motion control in machine tools[19].

CAD-PDM Information Exchange. Implementation of full-scale information management requires a substantial investment in time and money for planning, setup, and deployment. Some PC-based CAD tool vendors have begun to include essential components of PDM capabilities in their CAD tools. Capabilities of these tools include data vaulting, revision management, engineering change order processing and bill of materials (BOM) management, so as to help companies capture, share, and reuse the collective knowledge of their design engineering organizations.

It is expected that the emerging Product Life Cycle Support (PLCS) standard, ISO10303-239 (STEP AP239)[20], will provide a basis for all information exchanges involved in the full Computer-aided Product Realization (CAPR) process.

5. New Demands on Product Information Exchange

In this section, the major recent demands on product information exchange are discussed. Responses in terms of new or potential solutions are discussed in the next section.

Beyond Geometry. One of the most pressing demands expressed by all types of user organizations is to extend product information exchange beyond the geometry that is served by current CAD systems. This demand arises out of two complementary sources.

First, dealing only with the engineering design aspect of product realization, in essentially all the interchanges discussed in the previous section, non-geometric information has to be transmitted between collaborating entities and their support software systems:
o   In CAD-CAD and CAD-CAE interactions: material properties, boundary conditions, loads and their position, etc;
o   In CAD-CAD and CAD-CAM interactions: dimensions, tolerances, finishes, as well as bills of materials (BOM), etc.
Most of this information is either appended to the CAD geometry data in an ad-hoc fashion or transmitted separately and manually entered into the receiving software. Recently, a standard for Product Manufacturing Information (PMI) has been defined in ASME Standard Y14.41-2003 as the "Product Data Definition Standard."[21]

Second, concerns for interoperability and product information exchange, extending from the current emphasis on the engineering design phase of CAPD to encompass the entire product lifecycle of CAPR, introduce further demands for the capture and exchange of non-geometric information. For example,
o   in the early phases of product realization such as market research, requirements generation and even conceptual design, product information is primarily functional,

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[19] http://www.steptools.com/library/stepnc/index.html
[20] AP239 is in FDIS (Final Draft International Standard Stage).
[21] http://www.asme.org/codes/pr/y1441.html

rather than geometric; and

o in the latter stages of manufacturing, operation, use, maintenance and eventual disposal, the information on performance and behavior that needs to be collected to guide future versions of the product is again non-geometric.

The salient contexts in which demands for the capture and exchange of non-geometric information arise are briefly described in the following subsections.

Support for Feature-based Design. Features encapsulate various engineering characteristics. Over the past two decades considerable progress has been made in feature-based design [25]. However, traditional CAD systems were initially developed without the concept of features. Features were added only in the early 1990s. The consequence of this sequence is that features must refer to a piece of geometry, which limits the range of feature types that are supported. Furthermore, multifunctional features are typically not supported. Full support of feature-based reasoning throughout the product development process would need to handle:

o purely non-geometric entities, such as software embedded in mechatronic systems;

o non-geometric features of physical artifacts, such as those arising in the early phases of design before the geometry is defined; and

o multi-functional features (e. g., design, analysis, assembly and manufacturing features) and their transformations as the product design progresses.

Support for Knowledge-based Engineering. The term knowledge-based engineering is used in two senses. In one sense, it refers to any phase or aspect of the design process where the process is assisted or augmented by any process-related or reference information such as design rules, templates, catalogs, case libraries [11]. In a narrower sense, as used in Section 1, it refers specifically to the early, conceptual or preliminary phases of design, where symbolic and other non-geometric knowledge is used to synthesize an initial form from the functional requirements.

The information capture and exchange aspects of the two uses of the term are similar and center on three needs:

1. the capture, storage and retrieval of a much wider variety of information types than in other aspects of CAPD, such as tables, charts, formulas, spreadsheets, catalogs;

2. a common representation of "executable" knowledge such as rules and scripts independent of the particular expert system that is "driven" by this knowledge, which is not the case today; and

3. increased levels of security for the company-specific proprietary information expressed in the knowledge base above and beyond the security provided for the product information exchanged among the companies participating in the product delivery process.

A recent effort at the Object Management Group is addressing the interoperability among knowledge-based applications.[22]

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[22] http://mantis.omg.org/

Support for the Management of Product Variety. Managing variety and providing mass customization have become driving forces in organizing design and manufacturing organizations. Modular designs, platform based designs, common product architectures with substitutability, and plug and play capabilities are increasingly becoming the norm [26,27,28]. There are many efforts to adapt and extend traditional PDM and ERP systems for the support of this new environment, but a consistent solution for the full support of product representation and information exchange through all manifestations of product variety has not yet emerged.

Support for Product Lifecycle Management. Product Life Cycle Management (PLM) is a strategic approach to creating and managing a company's product-related intellectual capital, from the product's initial conception to its retirement and disposal. PLM entails the management of product design, manufacturing and service knowledge that goes beyond the interaction of suppliers with the system integrator. PLM reaches into the sales, customer service and product disposal activities that participate in the larger network. The concern in this paper is the information exchange support of PLM, which entails the modeling, capture, exchange and use of information in all PLM decision making processes. Without a comprehensive information base providing the information required by the different participants in the entire product lifecycle, overall efficiencies that can in principle be achieved in the network cannot be realized.

Various architectures for PLM support have been suggested [20, 29]. In all these architectures, the two major functions are: (1) support of information exchange among the enterprise nodes; and (2) support for data, information and knowledge integration within the nodes.

6. New Developments in Product Representation and Information Exchange

Two approaches are emerging in the area of information exchange support for Computer-aided Product Development (CAPD) as well as the entire Computer-aided Product Realization (CAPR) process:
o incremental extensions of existing CAD/CAE/PDM systems; and
o conceptual frameworks and architectures for new approaches.

The first approach is being pursued by most CAD/PDM software vendors and appeals because of its evolutionary nature. This approach tends to build on the vendors' existing proprietary representations and may therefore lead to ever more incompatible frameworks. There are strong trends, both among large integrated industries and among vendors, towards ever larger vertically integrated systems with proprietary information representations.

The second approach is being pursued by universities, research groups and some software vendors. This approach is based on the expectation that future CAPR infrastructures will be distributed and collaborative, where designers, process planners, manufacturers, clients, and others communicate and coordinate using a global web-like network. Participants will be using heterogeneous computing systems, information structures and information models, with differing formats and content across the disciplines. Hence,

appropriate standard exchange mechanisms will be needed for realizing the full potential of shared information models. The various tools will be coordinated by a Product Life Cycle Management (PLM) process or some future variant of it.

Due to space limitations, only two research and development projects in this category are summarized in this section. These two are representative of a large range of similar efforts. These projects go beyond the geometry representation of a product, where information is encoded in the form of ontologies; an ontology can be viewed as a set of objects connected through formally defined and computer-verifiable relationships. The entire field of CAPR support via PLM is still in a preliminary, pre-standardization stage.

The MOKA Project. A representative example of a product representation scheme for the support of CAPD beyond the geometry-based approach of traditional CAD systems is the ESPRIT-funded project known as MOKA [30]. MOKA provides two modeling options: 1) an informal model based on a structured, natural language representation of engineering knowledge using pre-defined forms; and 2) a formal model using UML-based graphical, object-oriented representation of engineering knowledge for artifact descriptions. The MOKA methodology intends to synchronize an artifact's lifecycle development process with the entire knowledge-based engineering (KBE) tool development lifecycle and to cover the entire gamut of engineering knowledge related to an artifact. Knowledge is grouped into two distinct categories: (1) product knowledge about the physical entity being designed; and (2) process knowledge about the steps taken to design the product. MOKA uses a term "Product Model" to describe a model of an entire product family. The MOKA Product Model supports five distinct views of a product, as follows:

1. **Structure** defines the hierarchical decomposition of a product's structure into parts, assemblies, and features. It can be either a physical, logical or conceptual structure at any stage of design.
2. **Function** defines the functional decomposition of the product and principles of solution.
3. **Behavior** includes a state model of the various states of a product and of the transition from one state to another.
4. **Technology** includes materials and manufacturing process information.
5. **Representation** includes any other user-defined technological information, including alternate representations of the physical structure such as Geometry and Finite Element Method (FEM).

MOKA is geared to support specific industrial implementations of CAPD and a number of industrial adoptions have been reported.

The NIST CPM Project and Extensions. The NIST Core Product Model (CPM) was initially conceived as a basis of future CAPD information exchange support systems [31]. It subsequently became clear that the CPM can serve as the organizing principle for supporting information exchange in CAPR by providing the core functionality for the full range of PLM support demands presented in Section 6.

CPM is a generic, abstract model with generic semantics, with meaningful semantics about a particular domain to be embedded within an implementation model and the policy of use of that model. The key concept that makes CPM a candidate for supporting the full range of PLM activities is that a product (denoted as artifact in CPM) is described by a triad:

1. **Function** models what the artifact is supposed to do. The term function is often used synonymously with the term *intended behavior*.
2. **Form** models the proposed design solution for the design problem specified by the function; in CPM, the artifact's physical characteristics are modeled in terms of its geometry (the "traditional" domain of CAD models) and material properties.
3. **Behavior** models how the artifact implements its function in terms of the engineering principles incorporated into a behavioral or causal model; application of the behavioral model to the artifact describes or simulates the artifact's *observed behavior* based on its form

The Open Assembly Model (OAM) extends CPM to provide a standard representation and exchange protocol for assembly [32]. The assembly model represents the function, form and behavior of the assembly and defines both a system level conceptual model and the associated hierarchical relationships. The model provides a way for tolerance representation and propagation, kinematics representation, and engineering analysis at the system level. OAM uses the model data structures of ISO 10303 discussed previously. The Product Semantic Representation Language (PSRL) utilizes CPM for the development of a formal representation of product information [33]. Formal description logic—DARPA Agent Markup Language (DAML) + Ontology Interface Layer (OIL)[23] -- is used to encode the PSRL. Mathematical logic and corresponding reasoning is used to determine semantic equivalences between the application ontology and the PSRL. Other extensions to CPM include support for modeling of heterogeneous material [34], mechatronic systems [35], and embedded systems [36].

CPM and its extensions are primarily conceptual information models; their success and utility will be measured by the type of implementation models that they influence.

7. Elements of Information Exchange: Content, Languages and Formalisms

It is impossible to predict the exact path or paths that product information exchange will follow in the next 25 years. Rather, we present in this section a conceptual model of the elements of product information exchange and their relationship so as to define the range of paths that may be taken.

The core of distributed engineering work and computing is the representation of the information *content* in terms of one or more *languages* using appropriate *formalisms*. The representations chosen for content are often governed by a number of orthogonal factors, including the degrees of expressiveness and scale needed for the exchange of content among the participants. Early CAD tools were driven by the need for efficiency

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[23] http://www.daml.org/

in encoding and presenting the content from the narrow perspective of creating machine generated drawings. Over time, the scope of content has changed as the number of participants and the scope of the product information has increased, as shown in Figure 3.
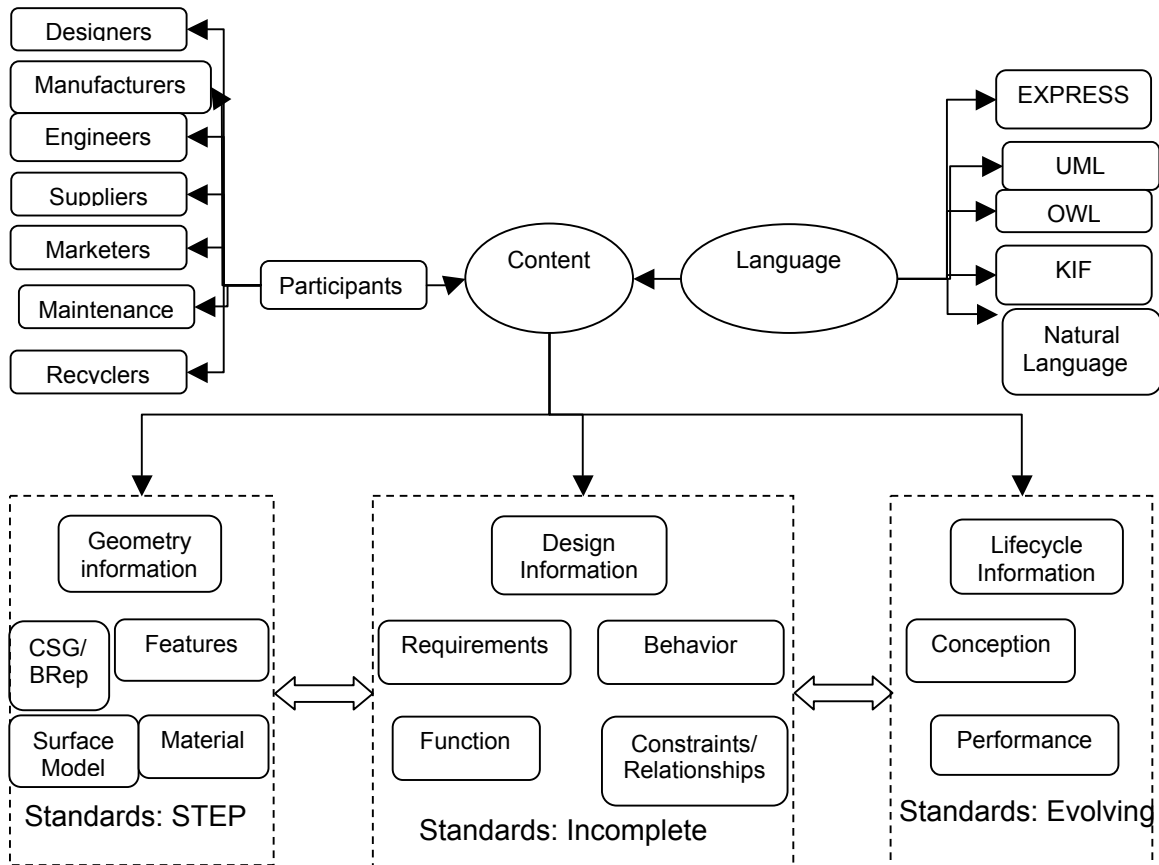
Figure 3: Content and Languages for Computer-Aided Product Realization

Elements of Information Content. The information content to be interchanged falls into three broad categories:
1. **geometry information** as discussed in Section 4;
2. **design information** including function, behavior, requirements, design rules, constraints, design rationale, etc.; and
3. **life cycle information** including initial concepts, product structure description, supply chain models, manufacturing plans and process information relevant to operations, maintenance, customer relationship management and product disposal.

Figure 3 shows the current status of standards pertaining to the three elements (denoted by STEP, incomplete, or evolving).

Languages. Figure 3 illustrates a representative set of languages that have been used or proposed for representing product information content. A language for information interchange is critically dependent on the shared vocabulary, syntax and the semantics that are expressible in the language. A spectrum of languages, from very expressive

natural languages to formal but semantically precise languages, provides the options from which to choose the language of exchange. The trade-off in the choices of representation will be driven by what and how much of the information needs to be captured and what is the effectiveness of the languages for the interchange of product information and knowledge across functional needs throughout the product life cycle.

Formalisms for Content. Product information content can be represented using a wide range of formalisms. Some of the available alternatives are shown in Figure 4 (courtesy Michael Gruninger, NIST). At the left end of the spectrum are glossaries and data dictionaries, which are informal mechanisms for describing the captured data. Although such schemes provide some formal organization to data, they are not easily amenable for seamless information exchange. In the middle are XML-based schemas, which provide further organization to the data. XML is becoming a widely accepted language for expressing non-graphical domain-specific information that can be manipulated using various web resources. However, XML by itself does not adequately capture the semantics or "meaning" of a domain. There are several types of semantics that need to be captured. Formal mechanisms, such as logic, generate domain-specific ontologies which encode the relationships of interest between data elements. The latter formalisms will aid in the generation of semantically validated data and information models, which can then be utilized for developing self-describing and eventually self-integrating systems [37].
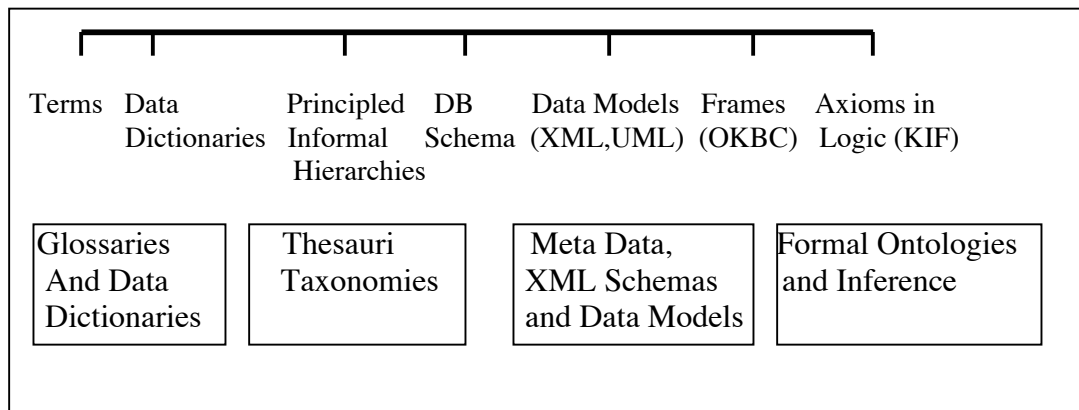

| Terms | Data Dictionaries | Principled Informal Hierarchies | DB Schema | Data Models (XML,UML) | Frames (OKBC) | Axioms in Logic (KIF) |

| Glossaries And Data Dictionaries | Thesauri Taxonomies | Meta Data, XML Schemas and Data Models | Formal Ontologies and Inference |

Figure 4: Content Formalism Spectrum

8. Summary

In the past quarter of a century, product information interchange has increased by many orders of magnitude in volume and, more significantly, in the scope of the contents. Proceeding from the initial point-to-point interchange of geometry information between isolated CAD tools through interchange of all design information, geometric as well as non-geometric, within and between information silos supporting product developments; we are approaching the interchange of the complete information and knowledge supporting the full product realization process in networked enterprises. The paper reviews this evolution of product information exchange and presents some of the demands produced by the expansion of the scope of the information that needs to be interchanged.

As discussed repeatedly in the paper, this vast expansion in the scope of the contents to be interchanged is closely followed by the development of standards governing the interchange. From the earliest days, there has been a competition between proprietary standards built on the vendors' proprietary representations and open standards allowing interchange between heterogeneous tools and computing systems. There is still not a clear indication of which direction industry as a whole will take.

Consensus-based open standards that will form the basis for the future global information exchange in a seamless manner will need work towards developing semantics-based approaches. We believe that this is an area ripe for research. Collaborative efforts by the industry, academia, and government should strive towards the development of semantically-rich information models leading to seamlessly integrated CAPD and CAPR systems.

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